Chiral magnons in altermagnets

1. **Chiral split magnon in altermagnetic MnTe**
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2. **Circular dichroism in resonant inelastic x-ray scattering: Probing altermagnetic domains in MnTe**
   Authors: D. Takegami, T. Aoyama, T. Okauchi, T. Yamaguchi, S. Tippireddy, S. Agrestini, M. García-Fernández, T. Mizokawa, K. Ohgushi, Ke-Jin Zhou, J. Chaloupka, J. Kuneš, A. Hariki, and H. Suzuki
   arXiv:2502.10809

3. **Systematic mapping of altermagnetic magnons by resonant inelastic x-ray circular dichroism**
   Authors: N. Biniskos, M. dos Santos Dias, S. Agrestini, D. Sviták, K.-J. Zhou, J. Pospíšil, and P. Čermák
   arXiv:2503.02533

Recommended with a Commentary by Atsushi Fujimori, National Tsing Hua University

In 2019, several theoretical studies predicted that momentum-dependent spin splitting of energy bands and associated anomalous Hall effect can occur *without spin-orbit coupling* in some *collinear antiferromagnets* such as the organic salt κ-(BEDT-TTF)$_2$Cu[N(CN)$_2$]Cl [1] and the rutile-type RuO_2 [2,3] and MnF_2 [4]. In these antiferromagnets, referred to as *altermagnets*, the spin-up and spin-down sublattices are not transformed to each other through a primitive translation vector but through a non-primitive translation vector plus a rotation. Thus, the altermagnet lacks time-reversal symmetry like a ferromagnet but unlike a conventional collinear antiferromagnet, whose ordered spin structure has time-reversal symmetry, i.e., invariant under the time-reversal operation followed by a primitive translation [5,6].

Altermagnets are promising materials for spintronic applications because the fully compensated spins eliminate stray magnetic fields and enable ultra-fast device operations, yet the inherent broken time-reversal symmetry may induce finite magnetization and allow us to control the spins via external magnetic fields [7]. The magnon spectra of altermagnets are similar to those of antiferromagnets because of the antiferromagnetic coupling between neighboring spins. However, the antiferromagnet-like magnon band is split into two magnon bands of opposite chiralities, corresponding to the two spin sublattices that cannot be converted to each other via time-reversal operation, as shown in Fig. 1 [8]. (In a ferromagnet, the chirality of a magnon propagating with certain momentum **q** is uniquely determined by the magnetization direction.) As the splitting of the magnon band and its sign change are dictated by symmetry reflected on momentum space, they occur in the same **q** region as the **k** region where the spin splitting of electronic energy bands occurs, as has been detected by ARPES [9]. The frequency range (> THz) of the chiral magnons is similar to that of antiferromagnetic magnons and, therefore, much higher than that of chiral magnons of ferromagnets (∼GHz). This also favors applications of altermagnets to ultra-fast spintronic devices.

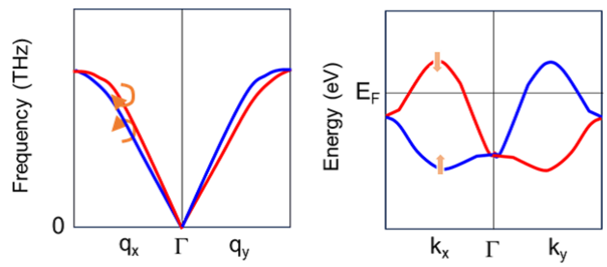

Figure 1: Chiral-split magnon bands in certain momentum **q** directions (left) and spin-split electronic energy bands in the same momentum **k** directions (right) of an altermagnet [8].

While many of the pioneering theoretical works mentioned above have been done on the rutile-type materials, particularly on RuO_2, magnetic ordering in RuO_2 has not been firmly established so far [10]. On the other hand, altermagnets having the hexagonal NiAs-type structure such as FeS, MnTe, and CrSb have attracted more recent interest. As shown in Fig. 2, the unit cell contains two metal atoms M1 and M2 with opposite spins. The spins are coupled ferromagnetically within the *a*-*b* plane and antiferromagnetically between the planes, i.e., between M1 and M2. The crystal structure is invariant under a $c/2$ translation followed by a 180° rotation around the c axis. The spin direction is either in the *a*-*b* plane (MnTe), perpendicular to it (CrSb), or flips between the two with temperature (FeS [11]). For the in-plane and out-of-plane spin directions, the Néel vector $\mathbf{L} \equiv \mathbf{M}1 - \mathbf{M}2$, where $\mathbf{M}1$ and $\mathbf{M}2$ are the sublattice magnetizations, can take six and two different values, respectively, resulting in six and two different magnetic domains.

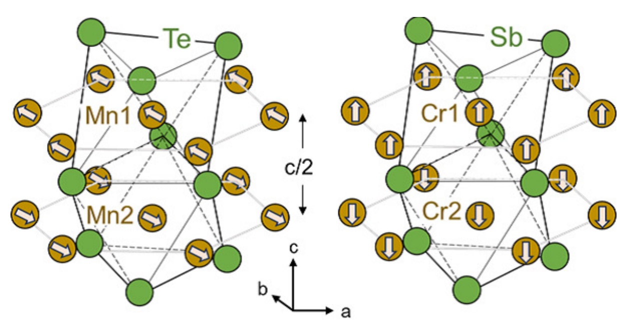

Figure 2: Collinear antiferromagnetic spin structures of the hexagonal MnTe and CrSb. Each of the Mn/Cr atoms are surrounded by six Te/Sb atoms forming an octahedron.

To study magnon spectra in solids, inelastic neutron scattering (INS) has been considered the most useful technique. In the first recommended paper, an INS study of chiral magnons in the hexagonal MnTe is reported. Owing to the high-energy resolution, a splitting of a few meV is clearly resolved in the high-energy part of the magnon dispersions, reflecting the chiral splitting shown in Fig. 1. The chiral nature of the splitting is demonstrated by a simulation using the linear spin-wave theory.

In the second and third recommended papers, the chirality of magnons in MnTe and CeSb [12] has been studied by resonant inelastic x-ray scattering (RIXS) measurements at the L_3 edges of Mn and Cr, respectively. RIXS is a new powerful technique to study magnons. A big advantage of RIXS is that one does not need single crystals of cm size necessary for INS but crystals of sub-mm size are sufficient. In the RIXS studies of both MnTe and CrSb, scattered signals are found to be dominated by those from one of the six and two single $\mathbf{L}$ domains, respectively. Utilizing the polarization switching of the incident x rays and the scattering angle θ_s and azimuthal angle ϕ dependences, i.e., the $\mathbf{q}$ dependence of the scattered x-ray intensity (Fig. 3), one can study chiral magnons in more detail. Although the energy resolution of RIXS is limited to $\sim$30 meV at best at the $3d$ transition-metal L_3 edges and is insufficient to resolve the chiral magnon splitting, the dichroic signals between the circular right and left polarized x rays, σ^+ and σ^-, reflect the magnon chirality as well as the direction of the scattered x rays with respect to $\mathbf{L}$.

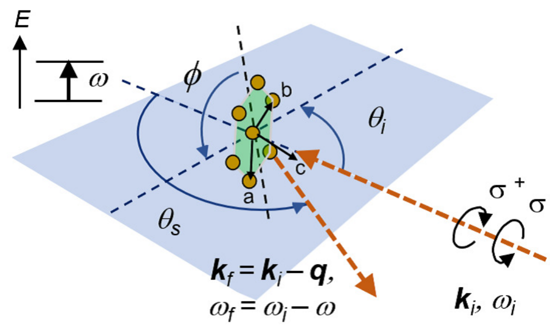

Figure 3: Experimental geometry of RIXS using circularly-polarized x rays, σ^+ and σ^-. θ_i is the incident angle relative to the sample surface, and θ_s is the scattering angle. ϕ is the azimuthal rotation angle of the sample around the sample surface normal. $\mathbf{q}$ and ω is the momentum transfer and the energy loss, respectively, from the incident x ray with momentum $\mathbf{k}_i$ and energy ω_i. The scattering plane is shown by light blue.

Finally, it is noted that the spin compensation in altermagnets is not guaranteed by symmetry. Therefore, small magnetization may be induced by perturbations such as lattice distortion [7, 13], curvature [14], and domain walls [12]. Spin-orbit interaction (SOI), which is not considered in the original idea of altermagnetism, also lead to spin canting and (very) weak ferromagnetism via (higher-order) Dzyaloshinskii-Moriya interaction [7, 15]. SOI may also induce different orbital magnetic moments at the M1 and M2 sites and induce finite magnetization. As RIXS is an experimental technique that is compatible with the application of various external perturbations, in combination with other x-ray techniques such as magnetic and non-magnetic circular dichroism in x-ray absorption spectroscopy (XMCD, XCD) [16, 17], it will give invaluable microscopic information about altermagnetism and related interesting phenomena.

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